TITLE

The Development of a Dynamic, Six-Axis Spine Simulator

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ABSTRACT

Background Context: Whilst a great deal of research has been completed to characterise the stiffness of spinal specimens, there remains a limited understanding of the spine in six degrees of freedom, and there is a lack of data from dynamic testing in six axes.

Purpose: This study details the development and validation of a dynamic six-axis spine simulator.

Study Design/Setting: Biomechanical study

Methods: A synthetic spinal specimen was used for the purpose of tuning the simulator, completing positional accuracy tests, and measuring frequency response under physiological conditions. The spine simulator was used to complete stiffness matrix tests of an L3-L4 lumbar porcine functional spinal unit. Five testing frequencies were used, ranging from quasistatic (0.00575 Hz) to dynamic (0.5 Hz). Tests were performed without an axial preload, and with an axial preload of 500 N.

Results: The validation tests demonstrated that the simulator is capable of producing accurate positioning under loading at frequencies up to 0.5 Hz using both sine and triangle waveforms. The porcine stiffness matrix tests demonstrated that the stiffness matrix is not symmetrical about the principal stiffness diagonal. It was also shown that whilst an increase in test frequency generally increased the principal stiffness terms, axial preload had a much greater effect.

Conclusions: The spine simulator is capable of characterising the dynamic biomechanics of the spine in six axes, and provides a means to better understand the complex behaviour of the spine under physiological conditions.

INTRODUCTION

In recent years the spinal implant sector has maintained greater growth than any other orthopaedic market [1]. This growth is leading to an increase in the number spinal devices becoming available. Pre-clinical testing is critical in determining the safety and suitability of any spinal device prior to clinical use [2]. Such a proliferation of devices makes it paramount that testing protocols are standardised [2,3] and assessment should be ideally performed in comparison with an equivalent device with proven clinical outcomes [3]. Presently, wear and fatigue testing are the only requirements a device must meet prior to clinical trials [4-6]. For a fair assessment of the functional characteristics of all types of devices, these requirements should be extended to include studies aimed at assessing the efficacy of each device under physiological loading and ranges of motion.

Stiffness matrix testing can characterise the mechanical behaviour of spinal specimens in six degrees of freedom using a position-based control system. There have been numerous studies, often using custom-developed testing machines, that have investigated both the spine, and spinal implants in-vitro [7-11]. However, there are few studies that have carried out such experiments in six degrees of freedom [12-16], few that have done so dynamically [17], and none that have characterised the full stiffness matrix dynamically. The aim of this study was to develop and validate a spine simulator that will provide a means of completing dynamic, six-axis stiffness matrix tests on spinal specimens.

MATERIALS AND METHODS

A custom spine simulator was developed that was capable of dynamically applying physiological movements in six degrees of freedom (Figure 1). A Zwick testing machine (HBT 25-200, Zwick Testing Machines Ltd., Leominster, England) provided axial compression-extension and axial rotation (TZ and RZ respectively). An XY platform was mounted on the dual axis actuator of the Zwick machine, providing anterior-posterior and medial-lateral shear (TX and TY respectively). A gimbal head was mounted underneath the XY platform, which provided rotations in lateral bending and flexion-extension (RX and RY respectively). A cranial specimen holder was fixed to the gimbal head, and a caudal specimen holder was fixed to the base plate via a six-axis load cell (AMTI MC3-A-1000, Advanced Mechanical Technology Inc., MA, USA).

The loading requirements for the spine simulator were based on the capability of similar apparatus described in the literature [7,10,11,14]. The range of motion (ROM) of each axis was maximised within the geometrical constraints of the base platform.

The TX and TY axes each comprised a parallel arrangement of two linear guide rails, each with two carriages (HSR25B2SS, THK UK, Milton Keynes, UK), driven with a zero-backlash ball screw assembly (BNK1202, THK UK) via a one-axis compression/tension load cell with a 500 N capacity (615, Proctor & Chester Measurements Ltd., Kenilworth, UK). The ball screws had a representative travel distance error of ±0.018 mm over the full scale and were driven by brushless motors (EC90, Maxon Motor UK Ltd., Finchampstead, UK) via zero-backlash couplings (GESM, Lenze Ltd., Bedford, UK).

The gimbal provided zero backlash rotations in both the RX and RY axis through a Maxon EC90 motor and Harmonic Drive Gear (HFUC-17-80-2UH-SP+EC90+HEDL5540, Harmonic Drive UK Ltd., Stafford, UK). The transmission accuracy and repeatability of the Harmonic Drive gears was 0.0025° and 0.0017° respectively. A torque transducer with a torque capacity of ±50 Nm (TRS, Proctor & Chester Measurements Ltd.) was mounted between each Harmonic Drive Gear and the position of load application.

The existing Zwick hydraulic testing machine had a load capacity and ROM of ±25 kN and ±50 mm respectively in the TZ axes, and ±200 Nm and ±45° respectively in the RZ axis. The TX and TY assemblies had a ROM of ±25 mm, and a load capacity of ±500 N. The RX and RY axes could provide a ROM of ±22.5°, and maximum continuous torque capacity of ±31 Nm.

Position and load control of the Z axes was achieved using Zwick Workshop 96 (Version 6.00, Zwick Testing Machines Ltd.). The remaining four axes were controlled in position mode using a dSPACE controller (ds1003, ds4001, ds2002, ds2103, dSPACE Ltd., Melbourn, UK) combined with four digital encoders (Maxon HEDL 5540) mounted on each motor in the X and Y axes, and four motor controllers (Maxon EPOS2 25/5). dSPACE Control Desk software (Version 2.3) was used for the user interface for the X and Y axes, and for the data acquisition system for all six axes.

The dSPACE controller used an open-loop system for position control. However, the individual Maxon motor controllers used closed-loop control. Analogue signals from dSPACE were input into the Maxon controllers, which moved the motors to the demand positions. An initial position control analysis was completed to ensure that the error between the demand and actual position was minimal.

Position Control Analysis

Five test frequencies were used to compare the demand position from dSPACE with the actual position in the Maxon controller software. A synthetic model of a functional spinal unit (FSU) with the facets removed was used during the tests, which provided a similar loading environment to the stiffness matrix tests.

The synthetic model comprised simulated vertebral bodies machined from cylinders of nylon and bonded to a nitrile rubber disc. The diameter of the specimen was 50 mm, the height of the disc was 10 mm, while that of the vertebral bodies was 25 mm. The specimen was potted into the specimen holders using low melting point alloy (MCP75, Mining & Chemical Products Ltd., Northamptonshire, UK). Care was taken to ensure that the disc was aligned with the horizontal plane. The height of the spine simulator was adjusted so that the origin of the displacement axes coincided with the centre of the disc.

Comparison tests of the demand and actual position were carried out for all four axes that used a Maxon motor: TX; TY; RX; and RY. The amplitudes tested were the same as those used by Stokes et al. [14] and as subsequently used in the stiffness matrix tests of the present study, as they are approximate general ranges of motion in the natural human disc during daily activities. These amplitudes were: 4° in RX and RY; 3 mm in TX; and 1.5 mm in TY. Both sine and triangle waves were tested at frequencies of 0.05, 0.1, 0.2, 0.5, and 1.0 Hz.

The frequencies were chosen to cover a wide range of physiological speeds. A frequency of 0.05 Hz was equivalent to 0.8°/sec in rotation. Slower speeds would have been difficult to assess, as the maximum length of data acquisition using the Maxon software was 12 seconds. The highest frequency of 1 Hz equated to 16°/second in rotations. Six cycles were separately recorded for the analysis of each axis, at each frequency, for both sine and triangle waveforms.

Spectral analysis was performed on the demand and actual position signals using Matlab (Version R2012b, MathWorks Inc., Natick, MA, USA). A one-way ANOVA with a Bonferroni post-hoc test was completed to compare the peak to peak (PTP) error between the demand position and the actual position at each test frequency for sine and triangle waveforms in the TX, TY, RX, and RY axes using SPSS software (IBM SPSS Statistics 19, IBM Corporation, Armonk, NY, USA).

Synthetic Specimen Stiffness Matrices

Following the demand and actual position comparisons, stiffness matrix tests were performed using the same synthetic spinal specimen. The aim of these tests was to ensure that the spine simulator was capable of completing stiffness matrix tests under loading conditions similar to those expected during biological tissue testing. The results from the synthetic stiffness matrix tests were compared to previously published data [12-15].

Stiffness matrix tests were completed at 0.1 and 0.5 Hz with an axial preload of both 0 and 500 N. These test frequencies approximated to dynamic speeds at the lower and upper range of those recommended for spinal testing by Wilke et al. [3].

For each test, 5 triangle wave cycles were completed in each axis whilst all other axes were held in a stationary position. Data were acquired at 100 Hz. The first two cycles were preconditioning cycles, and the last three cycles were used to compile the stiffness matrices. The stiffness was calculated for the centre of the superior vertebral body using rigid body transformations and the linear least squares method. This is the same method used previously in calculating stiffness matrices of spinal specimens [12-15]. However, unlike previous studies, symmetry about the principal stiffness terms was not assumed, resulting in four stiffness matrices, each composed of 36 stiffness terms (Table 1).

In order to compare the effect of test frequency and preload in the principal stiffness terms, the results were normalised, and the difference in stiffness calculated. The stiffness at a frequency of 0.1 Hz without an axial preload was used as the baseline stiffness, and thus given a value of 0%. Any increase or decrease in stiffness as a result of changed testing conditions would then be represented by a positive or negative percentage respectively. This method took into account negative stiffness values, which a standard normalisation method would not. This method of reporting normalised stiffness changes due to test frequency has previously been used by Costi et al. [17].

Porcine Pilot Study

Stiffness matrix tests were completed using an L3-L4 porcine FSU to compare the results of the spine simulator with previously published data. The primary aim of the pilot study was to assess the suitability of the testing protocol, and make any refinements prior to completing stiffness matrix studies using multiple specimens.

The porcine FSU was harvested from an organically farmed pig aged between eight and twelve months at the time of slaughter, and having a mass of approximately 60 kg (Bartlett & Sons Ltd., Bath, UK). The musculature was removed, whilst the ligaments and the facet joint capsules were left intact.

Three self-tapping screws were driven into the cranial and caudal ends of the specimen prior to being potted in specimen holders using a low melting point alloy (MCP75). Water-cooling of the specimen holders was used to prevent overheating of the specimen. Care was taken to ensure the alignment of the intervertebral disc with respect to the horizontal plane. The specimen was then wrapped in plastic film to minimise moisture loss. The specimen was mounted in the spine simulator with the centre of the intervertebral disc aligned with the origin of the displacement axes.

All testing was completed at room temperature (20±2°C). A total of 60 tests were completed, comprising one test for each of the six axes at 5 frequencies (0.00575, 0.05, 0.1, 0.3, and 0.5 Hz), with an axial preload of 0 N and 500 N. This resulted in a total of 10 stiffness matrices. The same ROM was applied in each axis as the previous tests using the synthetic specimen. The tests were completed first with 0 N preload. The axial translation axis was then set to load control and a 500 N load applied. This was maintained for 3 hours to equilibrate the specimen prior to the 30 tests with an axial preload of 500 N. This equilibration period was the same at that used by Stokes et al. [14] when completing similar stiffness matrix testing of a single porcine lumbar spinal unit.

The choice of testing frequencies was based on the need to allow comparisons with other studies and the necessity to evaluate the full frequency range of the spine simulator. Stokes et al. [14] used quasistatic testing, with a frequency of 0.00575 Hz. Therefore, this frequency was used to allow comparisons with their work. The frequency of 0.05 Hz was used, as this represented the lower end of dynamic testing speeds recommended by Wilke et al. [3]. The frequency of 0.1 Hz matched one frequency applied by Costi et al. [17] and the frequency used by Spenciner et al. [18]. A maximum frequency of 0.5 Hz was used as this represented the maximum velocity which, according to the control validation tests, the spine simulator could maintain accurate positioning. A fifth frequency of 0.3 Hz was chosen for completeness, representing an intermediate value between 0.1 Hz and 0.5 Hz.

Five cycles were completed for each test, with the first two being considered as preconditioning cycles. The stiffness was calculated at the centre of the superior vertebral body from the last three cycles using the linear least squares method. Symmetry about the principal stiffness terms was not assumed.

The effect of the 500 N preload on the specimen stiffness irrespective of the testing frequency was assessed using a Mann-Whitney test in SPSS software.

RESULTS

Position Control Analysis

The power spectral estimate of the demand and actual position signals demonstrated that in all four axes tested (TX, TY, RX, RY) and at all test frequencies (0.1, 0.2, 0.5, 1.0 Hz) there was only one excitation frequency, which matched the stimulation frequency from dSPACE. There were no resonant, vibrational, or noise frequencies present.

The error between the desired position and actual position generally increased as test frequency increased (Figure 2). The PTP and maximum errors were generally higher using triangle waves than sine waves but the mean error was similar for any given frequency. The PTP error was highest in the TY axis, which at a frequency of 1.0 Hz using a triangle waveform had a PTP error of 1.77% (0.053 mm of 3 mm PTP amplitude).

A good waveform was produced at frequencies up to 0.5 Hz in both sine and triangle waveforms. At 1.0 Hz the triangle waveform became more rounded in profile, and the actual position overshot and lagged behind the desired signal. The desired signal in the Maxon controllers also deviated marginally from a true sine or triangle wave at frequencies of 1.0 Hz, though the analogue output from dSPACE remained a true sine or triangle wave.

The statistical analysis of the PTP error showed that in all four axes under investigation the error at 1.0 Hz was significantly higher than all other test frequencies using the sine waveform ($p \leq 0.001$ in all cases). Using triangle waveforms the PTP error at 0.5 and 1.0 Hz was significantly higher than at lower test frequencies in all four axes ($p \leq 0.001$ in all cases), and the error at 1.0 Hz was significantly higher than at 0.5 Hz in the TY, RX, and RY axes ($p < 0.001$ for all cases).

The PTP error, and the mean error at a frequency representative of physiological situations (0.1 Hz) were much lower than at higher frequencies, and the waveforms were cleaner in profile. For triangle waves at 0.1 Hz the mean PTP error in the TX axis was 0.14% (0.008 mm over a 6 mm PTP amplitude), in the TY axis was 0.48% (0.014 mm over a 3 mm PTP amplitude), and in the RX and RY axes was 0.15 and 0.19% respectively (0.012 and 0.015° over a PTP amplitude of 8° respectively).

Synthetic Specimen Stiffness Matrices

Increasing the test frequency and applying an axial preload had the effect of increasing the stiffness of the specimen. The characteristics of the load-displacement curves differed between stiffness terms, with some exhibiting the S-curve of a neutral axis and elastic zone, and others (notably the principal shear stiffness terms $k_{1,1}$ and $k_{2,2}$) appearing linear with R^2 values greater than 0.99. Irrespective of the load-displacement characteristics, it was found that the three cycles over which the data were analysed were consistent for all stiffness terms. The compressive portion of the axial compression/extension tests at 0.1 and 0.5 Hz were used to estimate the Young's Modulus of the nitrile rubber disc of the synthetic specimen. A value was calculated for each of the three cycles used for analysis. The Young's Modulus was estimated to be 3-3.5 MPa, which is in the mid-range of published data of 2-5 MPa [19]. The range of calculated stiffness values between cycles was 0.05 and 0.06 MPa at 0.1 and 0.5 Hz respectively.

The addition of an axial preload of 500 N had more of an effect on the principal stiffness terms than an increase in testing frequency from 0.1 to 0.5 Hz (Figure 3).

The stiffness matrices exhibited some degree of symmetry, though some pairs of terms were asymmetric, and others changed in different ways with the application of a preload.

Porcine Pilot Study

The three cycles over which the stiffness terms were calculated for each test demonstrated consistent load and position data in all stiffness terms. An increase in the test frequency increased the stiffness in most of the principal stiffness terms both without (Figure 4) and with a 500 N preload (Figure 5). An increase in the test frequency tended to cause the principal stiffness terms to increase, with the exception of shear stiffness terms. With an axial preload of 500 N, the shear stiffness increased from 0.00575 to 0.05 Hz but remained approximately constant from 0.05 to 0.5 Hz.

The R squared values of the principal stiffness terms was generally higher with the application of the 500 N axial preload. Without an axial preload lateral bending had R squared values between 0.3 and 0.5. The measured torque in lateral bending was low without a preload (approximately ±2Nm), and there was a large neutral zone, which reduced the R squared value. In Axial compression/extension, and flexion/extension without a preload the R squared values were above 0.7, and in shear and axial rotation the values were above 0.9 for all test frequencies. All principal stiffness terms with the axial preload had an R squared value greater than 0.85 at all test frequencies, and in shear the value was always above 0.99.

The stiffness matrices were not symmetrical about the principal stiffness terms. This can be seen in an example matrices from the porcine specimen at a test frequency of 0.1 Hz without an axial preload (Table 2), and with an axial preload of 500 N (Table 3).

The statistical analysis showed that, irrespective of the testing frequency, the majority of stiffness terms increased due to the 500 N preload. Significant differences were found ($p<0.05$) in 20 of the 36 stiffness terms (Table 4), including all principal stiffness terms with the exception of that in axial rotation (Figure 6).

DISCUSSION

The aim of this study was to develop and validate a spine simulator that will provide a means of completing dynamic, six-axis stiffness matrix tests on spinal specimens. The testing on both synthetic and porcine spinal specimens allowed the symmetry of the stiffness matrices to be assessed. The measurement of dynamic stiffness matrices provides new data for a porcine spinal specimen.

Simulator Validation

The position tests demonstrated that the error between the desired and actual position achieved by the simulator generally increased as test frequency increased. This was expected and is likely to be caused by the inertia of the portion of the simulator in motion. The deviation of the desired wave signal in the Maxon controllers at 1.0 Hz may have been due to the sampling rate of the Maxon controller in processing the analogue input signal combined with the maximum allowable acceleration of the motor. A frequency of 1.0 Hz is likely to be too fast for spinal testing of such amplitudes. Wilke et al. [3] recommended a maximum testing speed of 5°/second for spinal testing, and even the lower test frequency of 0.5 Hz in the present study equated to 8°/second in rotational axes.

The TY axis produced the largest PTP error of 1.77% due to the small testing amplitude of ±1.5 mm compared to the other axes. The TX axis used the same drive system as the TY axis and the mean PTP error was similar in absolute terms (0.053 and 0.050 mm at 1.0 Hz using a triangle wave for the TX and TY axes respectively). At testing frequencies representative of physiological situations (0.1 Hz), the mean PTP error in all axes was below 0.5% of the PTP amplitude.

There are large variations in the magnitude of previously published stiffness data for porcine, and human cadaveric specimens [12-14,17,18,20]. The principal stiffness terms of the synthetic specimen compared reasonably with those data and provided an inexpensive means of tuning and measuring error on the spine simulator.

Stiffness Matrix Symmetry

Many of the non-principal stiffness terms of the stiffness matrix would be expected to be negligible due to sagittal plane symmetry. Gardner-Morse and Stokes [13] also reported that the stiffness $k_{3,1}$, relating to anterior/posterior shear under axial compression/extension was negligible. However, the magnitude of this term was not reported in the study. A large number of these terms were very low in the present study, including the stiffness term $k_{3,1}$, however, multiple samples would provide more data on this subject, and a means to quantify what might be regarded as negligible for the different stiffness terms.

It has also been proposed that the stiffness matrix should be symmetrical about the principal stiffness diagonal due to the conservation of energy, and the assumption that the material properties are linear [14,21], though this is based on infinitesimal strain theory. A more recent study by O'Reilly et al. [16] has reasoned that this would only be the case for small rotations, and that such an assumption does take account of the non-conservative nature of forces from the facets and ligaments that are present in the spinal joint.

The present study found that using the infinitesimal strain method also resulted in asymmetric stiffness matrices. This was the case in both the synthetic and porcine specimens. The stiffness values of the one human cadaveric FSU specimen published by O'Reilly et al. [16] are comparable in some principal stiffness terms to those published using the infinitesimal method . However, it is difficult to know whether differences that do exist are related to the stiffness calculation method, or the coupled way in which loads were applied by O'Reilly et al.

Dynamic Porcine Stiffness Matrices

Gay et al. [11] and Costi et al. [17] have shown that the testing speed has a significant effect on the stiffness of cadaveric spinal specimens. It was therefore expected that the stiffness of the porcine specimen would increase with the test frequency. This was found to be the case in many stiffness terms, though further testing using multiple specimens would be necessary to fully understand how testing frequency may affect the stiffness matrices of spinal specimens.

The effect of preload on the stiffness of spinal specimens has been well-documented [12,15], and the present study suggested that whilst testing frequency may have an effect on the stiffness of a specimen, particularly in lateral bending and flexion/extension, the effect due to axial preload is much greater.

The magnitudes of the principal stiffness terms of the porcine specimen were generally lower than published data from the quasistatic testing of porcine and human cadaveric FSU specimens [12-14]. However, some of the stiffness terms of these published results vary by an order of magnitude between an initial study with a sample of one porcine specimen [14] to larger studies, which tested over a smaller ROM [12,13].

The three studies above all tested specimens in a saline bath at a temperature of 4°C. Bass et al. [22] have demonstrated that the stiffness of the anterior longitudinal ligament (ALL) was significantly affected by temperature. At 4.4°C the ligament stiffness was approximately 45% greater than at 21.1°C, and over 100% greater than at 37.8°C. It is likely that other spinal tissue would be similarly affected by temperature. Wilke et al. [3] have recommended a testing temperature of between 20 and 30°C in order to replicate the in-vivo mechanical properties, without accelerating tissue degeneration through testing temperatures as high as 37°C. However, more recently, Costi et al. [17] have immersed specimens in saline fluid with protease inhibitors to minimise the putrefaction of biological specimens over time, which has led to specimens being tested at 37°C over long periods (approximately 44 hours).

The moisture condition can also affect the mechanical properties of the spine. Wilke et al. [23] reported that the ROM of air exposed and drip irrigated porcine or ovine specimens increased with the number of cycles completed to a greater extent than specimens wrapped and in saline moistened gauze and periodically sprayed with saline solution. Pflaster et al. [24] found that a saline bath caused the intervertebral disc to swell, and even after the application of a preload of 445 N for 7 hours, the disc remained 10% more hydrated than during specimen preparation. The same study showed that an unloaded specimen sprayed with saline and wrapped in plastic film showed little change in hydration over a 3 hour period. Costi et al. [25] have shown significant differences in the stiffness of ovine specimens tested in air compared to those immersed in saline at a temperature of 37°C. The present study used plastic film to minimise moisture loss due to evaporation but the integration of a fluid bath in future studies may be advantageous.

Another study by Costi et al. [17] measured the principal stiffness terms at various test frequencies of human cadaveric spinal units with the facets removed, though the location of stiffness calculation was not stated. The stiffness was calculated using a linear regression method, and asymmetry was taken into account in calculating stiffness terms. At 0.1 Hz, the principal stiffness terms in the present study relate reasonably well to those of human cadaveric specimens tested at 0.1 Hz with a 0.4 MPa preload (equating to an average of 600 N). The translational stiffness terms were lower in the present study, but lateral bending, and flexion/extension were similar (3.54 and 3.68 Nm/deg respectively in the present study, compared to 4.1 and 3.0 Nm/deg respectively measured by Costi et al.).

An estimate of the stiffness of human cadaveric spinal specimens without facets and without an axial preload can be made by inverting the flexibility data of Spenciner et al. [18], which used a testing frequency of 0.1 Hz. From plots of the results, it was estimated that the stiffness terms in lateral bending, flexion/extension, and axial rotation were approximately 121,000 Nmm/rad, 95,000 Nmm/rad, and 113,000 Nmm/rad respectively. These values are higher than those obtained in the present study without an axial preload but lower than those obtained with an axial preload.

Previous studies have used linear regression to calculate the stiffness of spinal specimens in six axes [12-15,17], and the R squared values in the present study suggest that this is reasonable. More accurate stiffness measurement may be achieved in future studies by increasing the number of terms in the stiffness matrix to account for the asymmetry in the positive and negative directions of some movements, for example flexion and extension. Additionally, completing stiffness matrix tests of isolated vertebral bodies and the intervertebral disc would remove coupling effects of the posterior structures of the spine.

The comparisons above suggest that porcine spinal specimens may be similar to human cadaveric specimens in the principal stiffness terms with the exception of in axial rotation ($k_{6,6}$). Porcine specimens may therefore provide a means of further understanding spine biomechanics without the difficulties associated with human cadaveric testing.

CONCLUSIONS

The present study has demonstrated that a custom-developed spine simulator is capable of performing dynamic stiffness matrix tests on spinal specimens over physiological ranges of motion, without and with the application of an axial preload. The results obtained compare reasonably with previously published data, though a multi-specimen study would allow further comparisons to be made.

The stiffness matrix method provides the means to characterise the mechanical properties of a specimen in six degrees of freedom. However, applying complex multi-axis motions on a spinal specimen may further increase our understanding of spine biomechanics. The spine simulator developed in the present study is capable of cycling each axis simultaneously at independent ranges of motion and frequencies, and future studies may incorporate such testing methods.

The variation in published data in this research area emphasises the need for more standardisation in spinal testing, particularly in regard to specimen hydration, testing temperature, test frequency, and the method and magnitude of axial preload applied to specimens. However, the spine is a complex structure, and it may be difficult to reach a consensus on the most suitable testing methods for biomechanical evaluation of the natural spine, and of instrumented spinal specimens. It is hoped that further research using this spine simulator will provide steps toward such a goal.

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LIST OF FIGURES

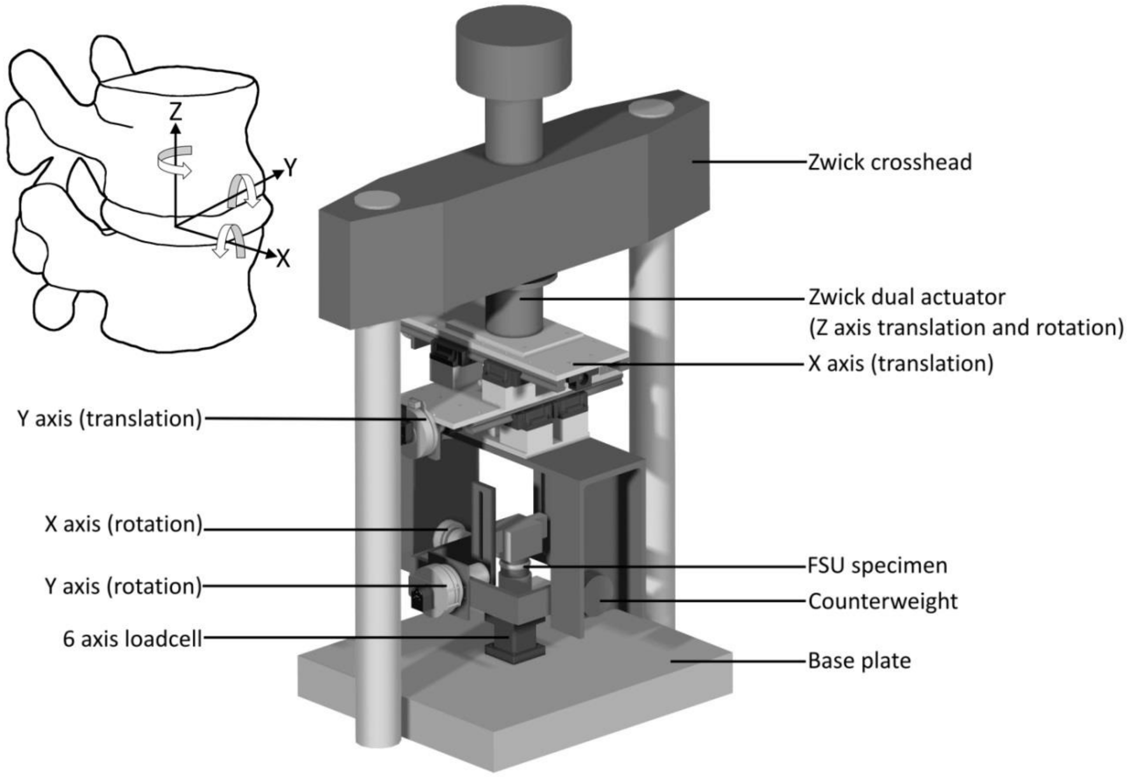

Figure 1: The spine simulator design

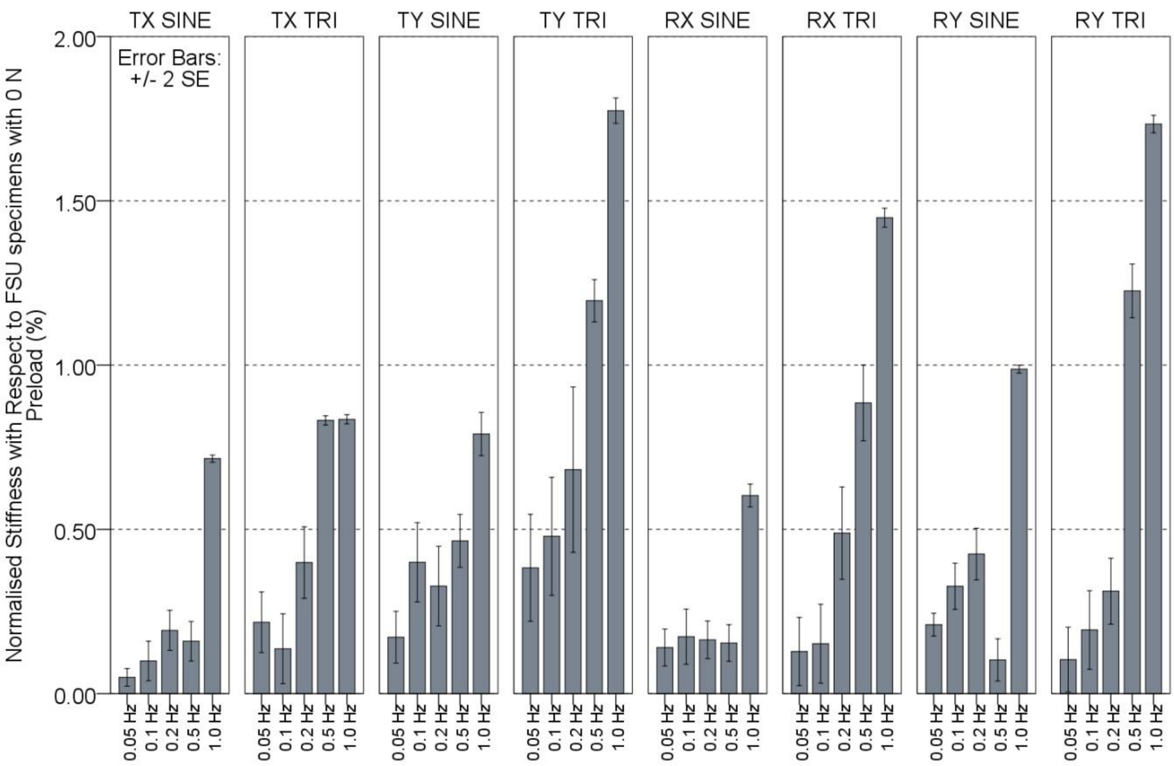

Figure 2: Mean and standard error of the peak to peak error (%) of the TX, TY, RX, and RY axes

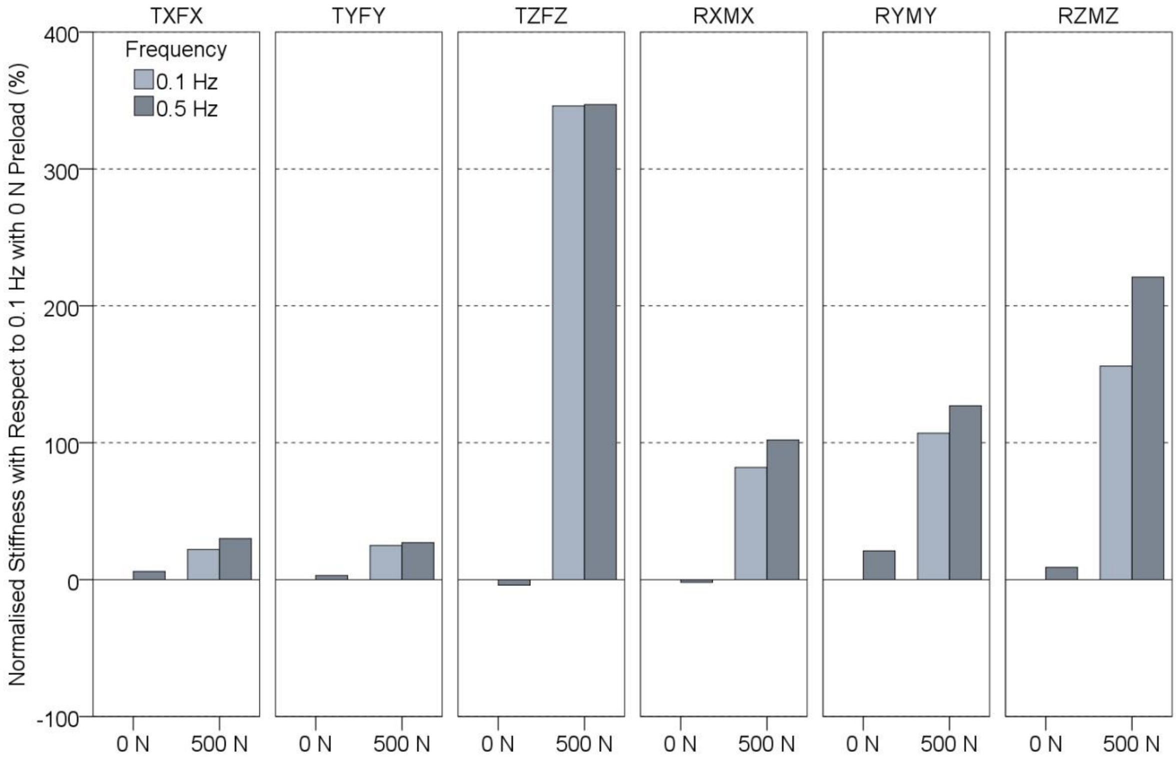

Figure 3: Difference in principal stiffness due to test frequency and preload, normalised to 0.1 Hz and 0 N preload

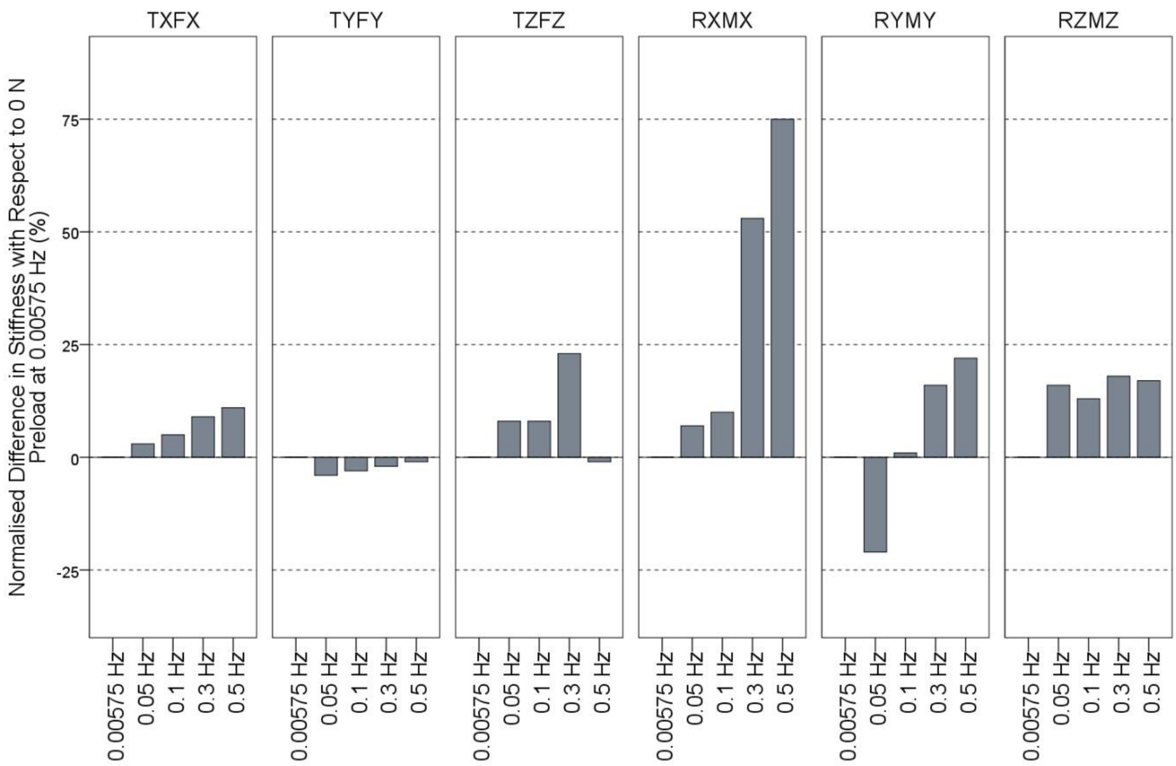

Figure 4: Difference in principal stiffness due to test frequency with a preload of 0 N, normalised to a test frequency of 0.00575 Hz

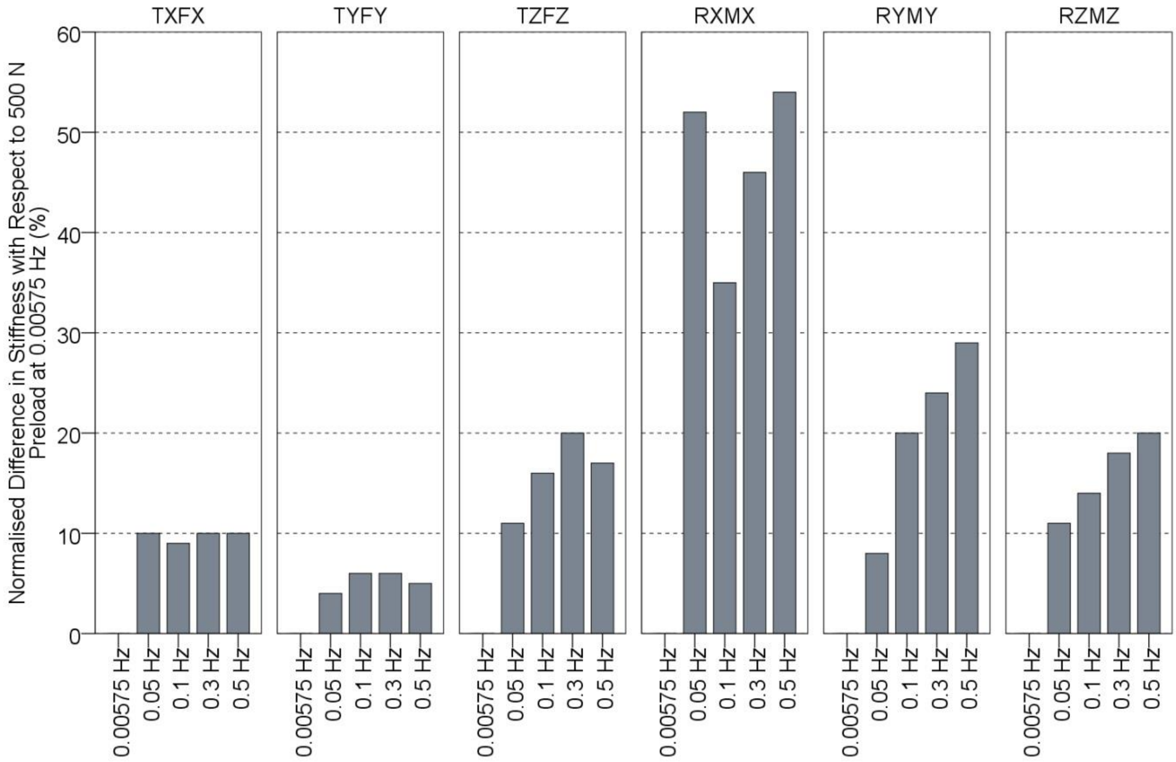

Figure 5: Difference in principal stiffness due to test frequency with a preload of 500 N, normalised to a test frequency of 0.00575 Hz

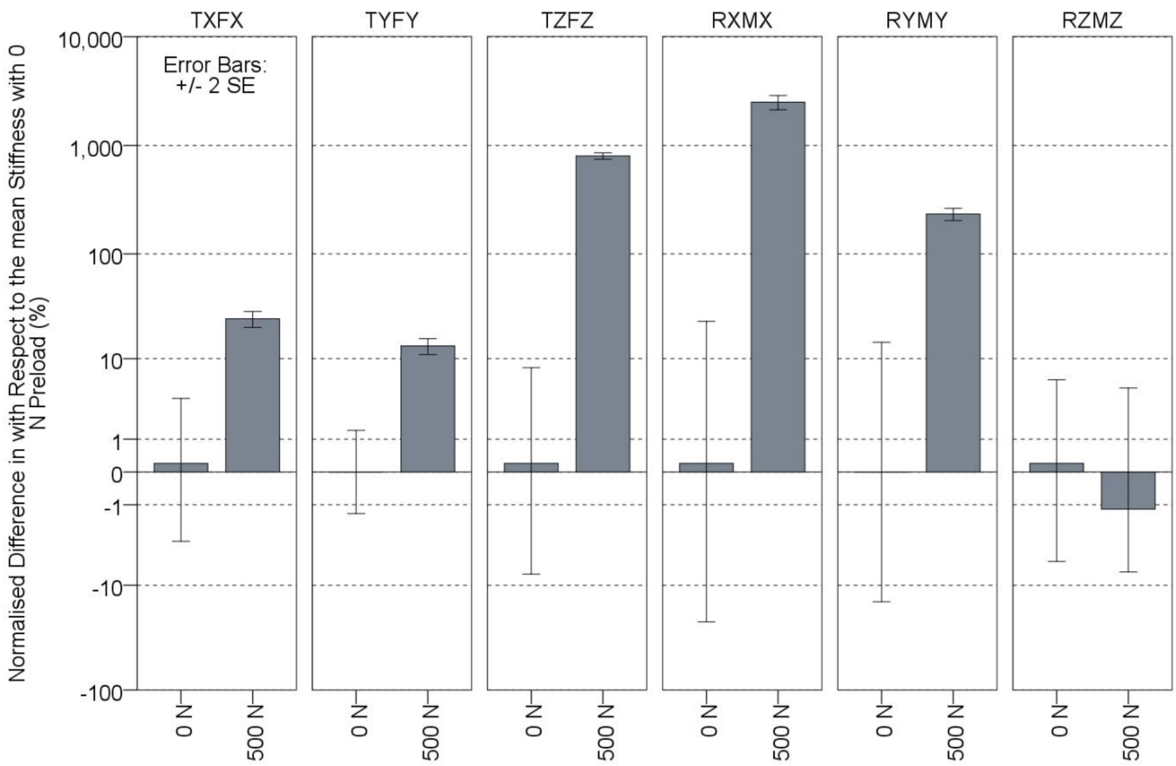

Figure 6: Difference in principal stiffness due preload irrespective of test frequency, normalised to the mean stiffness with a 0 N preload. Note the logarithmic scale

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Table 1: Stiffness matrix with principal stiffness terms in bold, and stiffness terms expected to be negligible due to sagittal plane symmetry in grey. Stiffness terms are derived from a displacement (TX, TY, TZ) or rotation (RX, RY, RZ) and an associated force (FX, FY, FZ) or moment (MX, MY, MZ).

	TX	TY	TZ	RX	RY	RZ
FX	$\mathbf{K_{1,1}}$	$K_{2,1}$	$K_{3,1}$	$K_{4,1}$	$K_{5,1}$	$K_{6,1}$
FY	$K_{1,2}$	$\mathbf{K_{2,2}}$	$K_{3,2}$	$K_{4,2}$	$K_{5,2}$	$K_{6,2}$
FZ	$K_{1,3}$	$K_{2,3}$	$\mathbf{K_{3,3}}$	$K_{4,3}$	$K_{5,3}$	$K_{6,3}$
MX	$K_{1,4}$	$K_{2,4}$	$K_{3,4}$	$\mathbf{K_{4,4}}$	$K_{5,4}$	$K_{6,4}$
MY	$K_{1,5}$	$K_{2,5}$	$K_{3,5}$	$K_{4,5}$	$\mathbf{K_{5,5}}$	$K_{6,5}$
MZ	$K_{1,6}$	$K_{2,6}$	$K_{3,6}$	$K_{4,6}$	$K_{5,6}$	$\mathbf{K_{6,6}}$

Table 2: Matrix P03, 0.1 Hz, 0 N preload (N, mm, rad)

	TX	TY	TZ	RX	RY	RZ
FX	**28**	2	3	-11	245	-55
FY	-1	**35**	-4	-168	-4	304
FZ	2	-6	**146**	6	-2,785	-118
MX	-117	838	18	**6,755**	1,341	1,581
MY	-663	-207	-1,485	338	**59,725**	-1,570
MZ	-67	-70	-558	-3,724	-103	**77,120**

Table 3: Matrix P08, 0.1 Hz, 500 N preload (N, mm, rad)

	TX	TY	TZ	RX	RY	RZ
FX	**36**	2	-25	-14	269	-25
FY	-2	**40**	9	-177	-65	239
FZ	26	2	**1,350**	-1,275	-9,050	-445
MX	-101	823	-13	**202,884**	-3,684	3,661
MY	-1,373	-257	-16,589	14,135	**210,631**	-4,137
MZ	-145	121	-522	40	-3,604	**76,788**

Table 4: The significance of preload on specimen stiffness using Mann-Whitney tests, statistically significant stiffness terms shown on grey ($p<0.05$)

	TX	TY	TZ	RX	RY	RZ
FX	**0.008**	0.151	0.008	0.421	0.056	0.008
FY	0.008	**0.008**	0.008	0.421	0.008	0.056
FZ	0.151	0.151	**0.008**	0.008	0.008	0.008
MX	0.421	0.421	0.222	**0.008**	0.008	0.056
MY	0.008	0.690	0.008	0.151	**0.008**	0.310
MZ	0.016	0.008	0.690	0.008	0.008	**0.841**